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DOWNEY PLANT

ORDNANCE DIVISION

PULSE-SENSITIVE ELECTROEXPLOSIVE DEVICES

Contract N178-8107

A Summary Report for Phase I

to

Naval Weapons Laboratory
Dahlgren, Virginia

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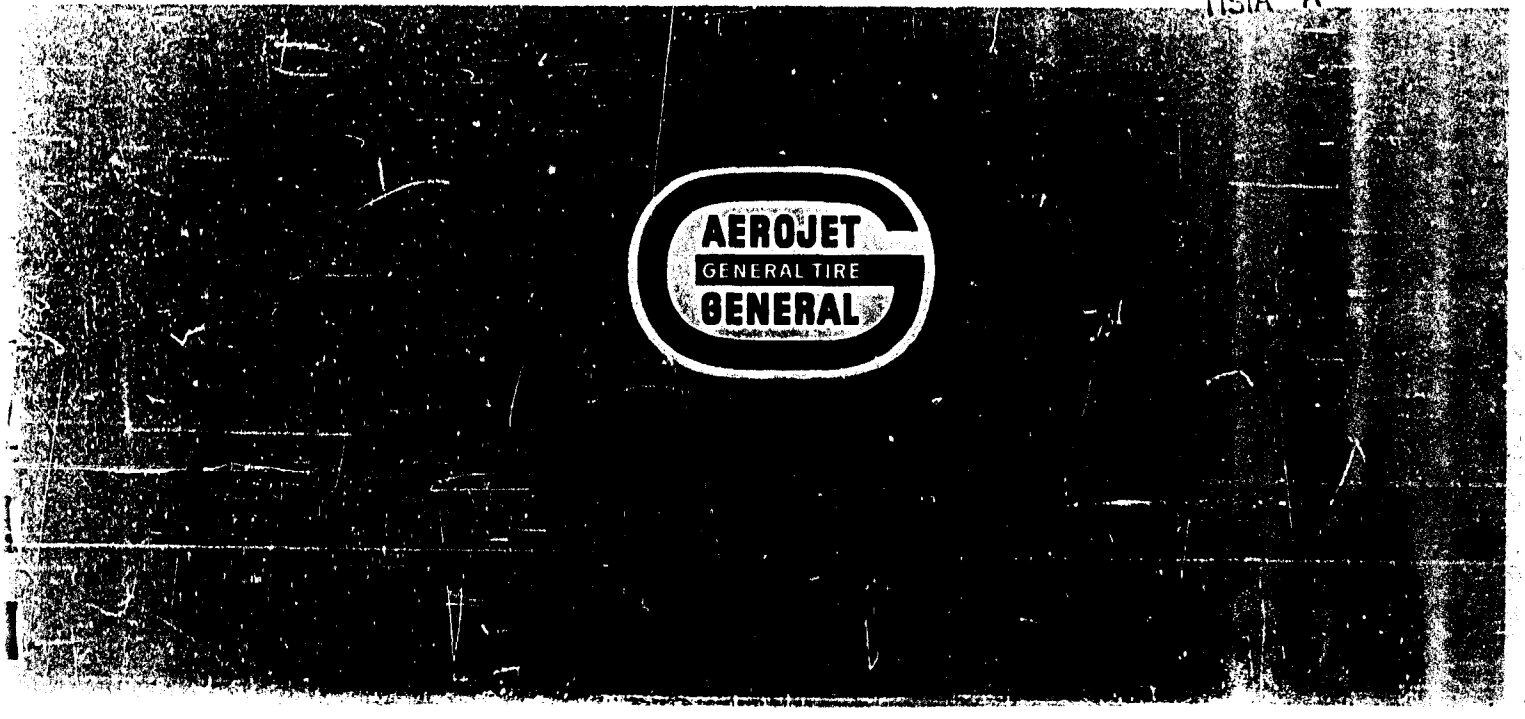

AEROJET-GENERAL CORPORATION
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PULSE-SENSITIVE ELECTROEXPLOSIVE DEVICES

Summary Report for Phase I

The Feasibility Study and Process Development

0689-01(10)FP

Contract: N178-8107

Naval Weapons Laboratory
Dahlgren, Virginia

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PULSE-SENSITIVE ELECTROEXPLOSIVE DEVICES

1. INTRODUCTION

Studies made under the Hazards of Electromagnetic Radiation to Ordnance (HERO) program resulted in an investigation of a pulse-sensitive electroexplosive device (EED) using a lower power sensitivity than exploding bridgewire devices. The theory of the operation is based on the high thermal conductivity of beryllium oxide ceramic (approximately that of aluminum). This report is a summary of Phase I, the Feasibility Study and Process Development portion of the investigation being carried out by the Aerojet-General Corporation at Downey, California.

Initiation of an explosive material is the result of introducing energy into the material to the point at which a self-sustaining exothermic reaction occurs. The most common method of energy introduction is the application of thermal energy, generally obtained by the heating of a resistance element or bridgewire by an electric current. An electrically heated bridgewire, however, is not only susceptible to heating from the intended firing current but is also susceptible to heating by stray currents from electromagnetic fields of radio and radar. It thus acts as a focal point for the energy that is led into it from external sources. This latter condition can possibly result in accidental initiation of the EED.

The Phase I study was to determine the feasibility of constructing a device capable of dissipating stray undesirable energy into a heat sink but still capable of being ignited by means of a fast electrical pulse. The design of a unit incorporating a heat sink presents the problem of supplying sufficient heat energy to the explosive interface for initiation of the primer material while maintaining the heat-sink characteristic for dissipation of heat energy resulting from RF energy fields or other stray spurious pulses.

The configuration considered is a thin metal film bridge in intimate contact with a beryllium oxide (BeO) heat sink. Stray sublevel pulses and currents are dissipated in the heat sink, and firing is effected by a fast and extremely high-level current pulse heating the film bridge.

With these considerations, comparative evaluations were made with wire-bridged and film-bridged conventional glass header units and with film-bridged BeO header units.

2. EXPLOSIVE IGNITION

Pertinent to electroexplosive devices are the characteristics of ignition of an explosive material. It has been shown that higher heat-source temperatures reduce the induction time for ignition (References 1, 2, and 3). Based on thermal conduction, this is to be expected. Assuming the ignition is effected by some given amount of energy per unit volume of the explosive, this energy will be transferred into the explosive at a rate dependent upon the temperature differential between heat source or bridge and the receptor or explosive. The higher the source or bridgewire temperature, the faster will the critical point for ignition be reached. As faster heating rates are applied, a point may possibly be reached at which the bridge will burn out and the current flow will cease before sufficient energy can be transferred to the explosive to cause ignition. Such a condition has not been experimentally proved, possibly because at the time of or following bridge burnout, arcing occurs. The temperature of such an arc is known to be exceedingly high, and it may be a means of energy transfer, resulting in ignition.

The program approach has been to use a conventional header configuration with beryllium oxide ceramic for its heat-sink qualities (instead of glass) and to apply a metal film bridge on the surface in place of the usual wire bridge.

3. BERYLLIUM OXIDE (BERYLLIA)

3.1 UNIQUE PROPERTIES

Beryllium oxide or beryllia is a ceramic material which is unique in that it has the electrical insulating property of ceramic materials but the thermal conductivity of a metal. These characteristics are the reason for its use in this study.

Information received from the National Beryllia Corporation on the relation of beryllium oxide purity to thermal conductivity indicates a substantial drop in conductivity for relatively small amounts of impurities. The following values are quoted from a National Beryllia Corporation technical data sheet dated September 1962: "Decreasing the beryllia content from 100 to 99% results in a 15 to 20% decrease in thermal conductivity. Decreasing the beryllia content from 100 to 98% results in a 20 to 25% decrease in thermal conductivity. Decreasing the beryllia content from 100 to 96% results in a 30 to 40% decrease in thermal conductivity. Decreasing the beryllia content from 100 to 90% results in a 50 to 60% decrease in thermal conductivity. The thermal conductivity given for 100% beryllia is 0.64 K cal/cm^2 sec°C cm."

Based on this information, experimental beryllia headers with a 99.5% purity and 95% density were ordered to obtain the higher thermal conductivity characteristics. Experimental glass headers of similar dimensions were also procured for comparative analysis. A header unit similar to a conventional header, except that the glass insulating material was replaced with BeO,was fabricated by the National Beryllia Corporation. Figure 1 is a drawing of the header.

3.2 BERYLLIUM OXIDE TOXICITY

Beryllium and beryllium compounds can cause serious illness and have been responsible for fatalities (Reference 4). BeO is dangerous when it enters the respiratory system, although on a weight basis, the oxide (BeO) is less toxic than beryllium itself. Skin reactions are not a problem in ordinary use of the ceramics. The processing of beryllium ores and alloys presents considerable hazard. Production of BeO ceramics is less hazardous. When BeO ceramics are machined or metallized, the hazard is even less, although still definitely existing. The handling of hard-fired BeO presents no hazard.

Beryllium compounds must be in the form of airborne particles to enter the respiratory system. Air contamination can occur if beryllia ceramics are heated above 1850°F in the presence of water vapor, or if small enough particles are mechanically produced from the solid. Conventional brazing in a dry atmosphere at safe temperatures presents no hazards.

The use of this material in an electroexplosive device will involve high temperature from ignited explosives as well as mechanical effects from the explosion. Currently no information has been found as to the degree of hazard produced by the temperatures and shock involved in an explosion. It is therefore advisable to use the utmost caution until the degree of hazard is established. In this program, the beryllium oxide electroexplosive devices are fired in a closed chamber (a modified pressure cooker) placed within an explosive test chamber equipped with a filtered exhaust system (Cambridge Filter-Blower Unit Model 2A65). Adequate precautions are taken in cleaning the chambers and filter system. The material is not disposed of by conventional methods. Waste materials must be sealed in containers and disposed of in the same manner as radioactive wastes. The Atomic Energy Commission states that the inplant concentration over an 8-hr day should not exceed 2 $\mu gm/m^3$ of air, and momentary exposure should not exceed 25 $\mu gm/m^3$. Aerojet personnel working on this program have been given blood tests and chest X-rays, and will be periodically examined.

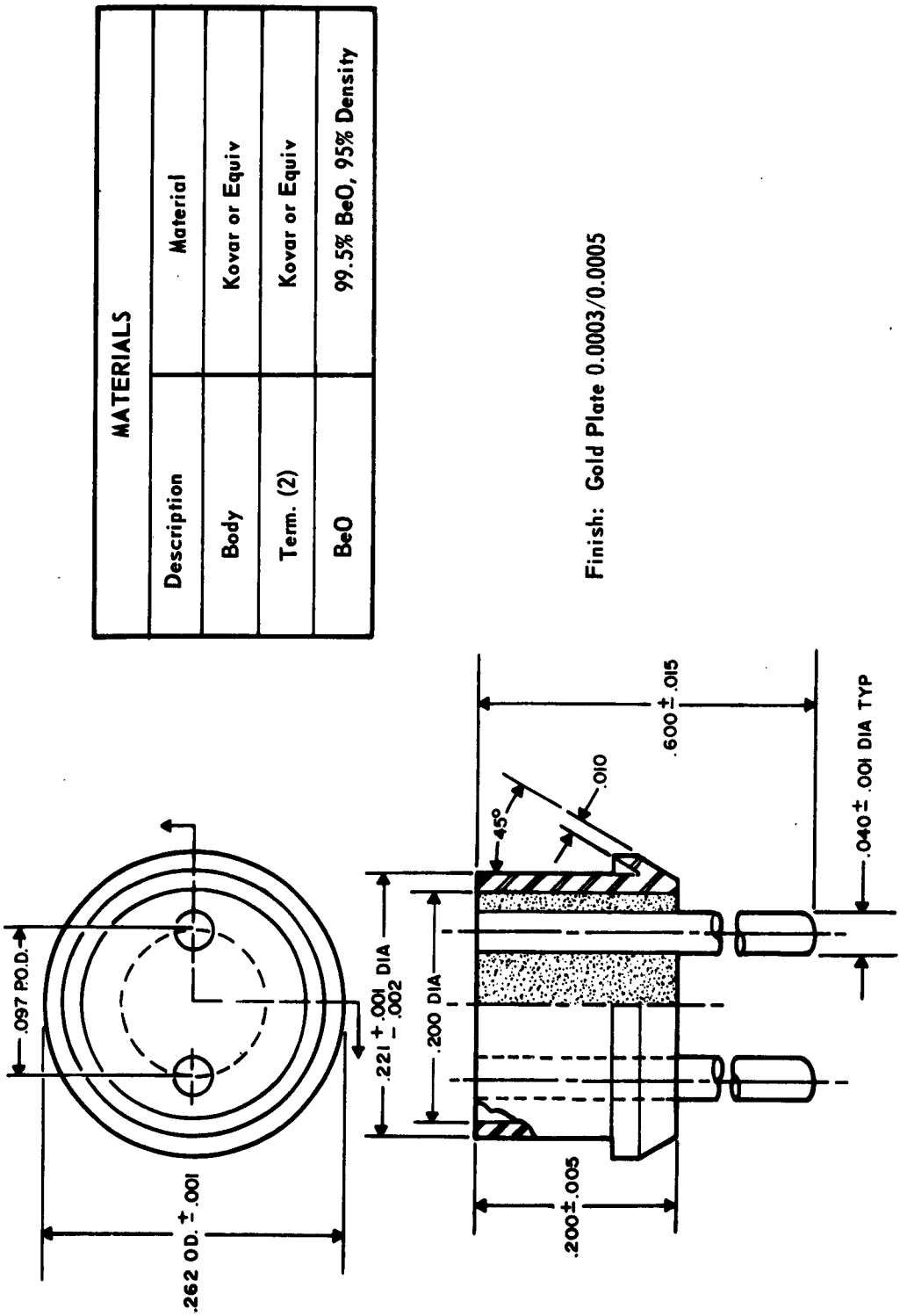


Figure 1. Experimental BeO Header Drawing.

4. METAL FILMS

Various methods are available for producing thin films (References 5 and 6). The following methods have been considered for an electrically heated metallic film bridge:

a. Chemical precipitation

b. Thermal decomposition on a heated substrate of a metal salt solution followed with electrodeposition to increase film thickness

c. Cathodic sputtering of metals

d. Vacuum evaporation of metals

Selection of a method depends on the materials involved, and cost. In an electroexplosive device, certain materials are immediately rejected as being incompatible with commonly used explosives. For example, lead azide in the presence of copper and moisture forms copper azide. Copper azide is more sensitive than lead azide.

The chemical-precipitation method is chiefly used for producing silver films over large surfaces. This method was rejected because of the incompatibility of silver with some explosives, particularly under production conditions. For example, lead azide with silver will form silver azide which is slightly more sensitive (Reference 7).

The thermal decomposition of a metal salt deposits an extremely thin film which would require building up with additional metal by electrodeposition or plating. Since several operations are involved, other methods seem more economical.

Cathodic sputtering and vacuum deposition seem the most promising methods. The pressure range for cathodic sputtering is 10^{-2} to 10^{-1} Torr and for vacuum evaporation 5×10^{-4} Torr or less. If the required low pressure can be attained, film deposition is more rapid by vacuum evaporation, and this is a more versatile process.

Briefly, cathodic sputtering is the disintegration of an electrode under bombardment of ionized gas molecules. The disintegrated material leaves the electrode surface either as free atoms or in chemical combination with the

residual gas molecules in the chamber. Some of the liberated atoms are condensed on surfaces surrounding the cathode; others are returned to the cathode by collision with gas molecules. It is difficult to prepare metal films free from oxide contamination by cathodic sputtering. The heat produced in the substrate with this method may also be greater than during vacuum deposition.

Vacuum deposition is the process of vaporizing a material in a low-pressure environment. The vapor molecules travel in an essentially straight path and are deposited on the work or substrate material. A simple thin mask over the work controls the area of film deposition. The maximum practical thickness of an evaporated deposit is about 1 μ. A wide range of metals and compounds may be evaporated and deposited in this manner. Vacuum deposition is used in this program to form film bridges in the electroexplosive device. Gold is used as film material because it deposits easily as a film and is compatible with currently used explosives.

The adhesion of a deposited film on a substrate material or base depends on the film and substrate materials and the cleanliness of the substrate surface. The headers, both of glass and BeO, were cleaned in an ultrasonic cleaner (Narda Ultrasonics Corporation Model G-601) using a bath of isopropyl alcohol for 10 min and allowing the units to air-dry on removal from the bath. Ionic-bombardment cleaning is then used in the vacuum chamber prior to metal deposition. A potential of 4500 v is applied between an aluminum electrode and the aluminum-header supporting fixture when the vacuum chamber is at a pressure of 200 to 500 μ. In ionic-bombardment cleaning, a high-voltage glow discharge passes between metal electrodes in the continuously exhausted vacuum chamber. The ions strike the surfaces, removing atoms or molecules which may combine with them. Combined ions and atoms are then removed from the system by the continuous pumping. The ion bombardment is very complex and no single satisfactory theory of the cleaning mechanism can be postulated. The method is universally used for cleaning substrate surfaces. The electrodes used for ionic-bombardment cleaning are generally aluminum, because this metal has a much lower sputtering rate than any other metal.

4.1 SELECTION OF METAL FOR FILM BRIDGE

A number of metals were investigated for use in making the film bridge. Preliminary vacuum-deposition tests were made with platinum, iron, nickel, gold, and aluminum. Gold and aluminum were selected for film-bridge testing because of their explosive compatibility, ease of deposition,

adhesion to the substrate, and relatively low tensile stresses of evaporated deposits, as well as availability. Aluminum has better adhesive characteristics than gold. However, the aluminum films tested had lower resistance values after sublevel firing-pulse currents were applied; and when these films were observed in a darkened room, minute arcs or flashes could be seen. This effect is probably the result of oxidation from residual air in the vacuum system, and surface oxidation of the first film deposit in the two-step procedure employed (Section 4.2.2).

4.2 FILM-BRIDGE DEPOSITION

4.2.1 Preliminary Study

The first film depositions were made over the glass header surfaces, then cut to form a strip film bridge between the two connecting pins. Pulse-current tests showed film breakdown at the edges of the connecting pins as shown in Figure 2. Tests were made with some success with the bridge shaped or narrowed in the central region as shown in Figure 3. However, some of the units still burned out at the edge of the connecting pins (Figure 4). Subsequent experimentation led to a double deposition process that produced a thicker double film deposit in the region of the connecting pins, and a single thin deposit in the central area between pins.

4.2.2 Film-Bridge Deposition Process

The film-bridge deposition procedure was developed using glass header units. The headers are first cleaned in an ultrasonic cleaner with isopropyl alcohol for 10 min. They are then dried in air for approximately 15 min and mounted in an aluminum holding block with appropriate masks of aluminum foil and wire to form the desired rectangular film pattern (Figures 5 and 6). The aluminum blocks on the supporting fixture are shown in Figure 7, and a view of the assembly within the vacuum chamber in Figure 8. The central region is masked with an 0.020-in.-diameter aluminum wire for the first film deposition. The gold film is deposited on the header by evaporation from a heated tungsten boat at a chamber pressure of approximately 1×10^{-4} Torr. After the first film deposition the header mounting blocks are removed from the vacuum system, the central masking wire is removed (Figure 9), and the unit is again placed in the vacuum system to receive a second film deposit. Thus a rectangular film bridge is deposited, connecting the ends of the two pins and in intimate contact with the substrate. The central region between pins is thinner and is therefore the region where maximum heating will occur.

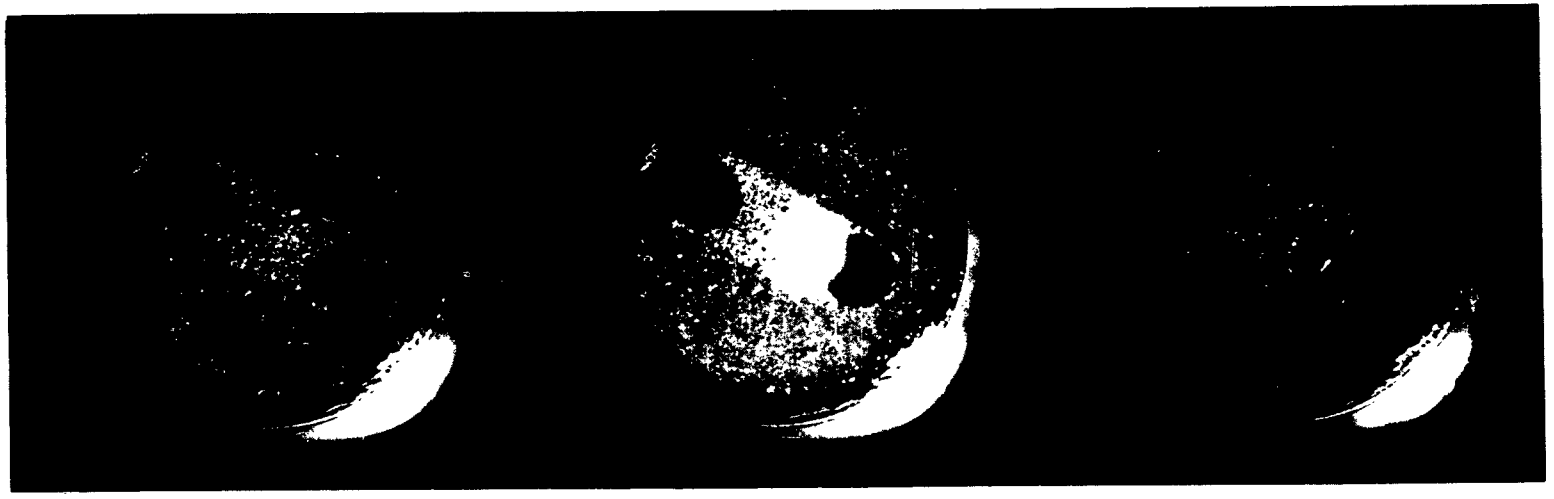


Figure 2. Glass Header Unit Before, During, and After the Heating Pulse.
(Magnification 10 Diameters)

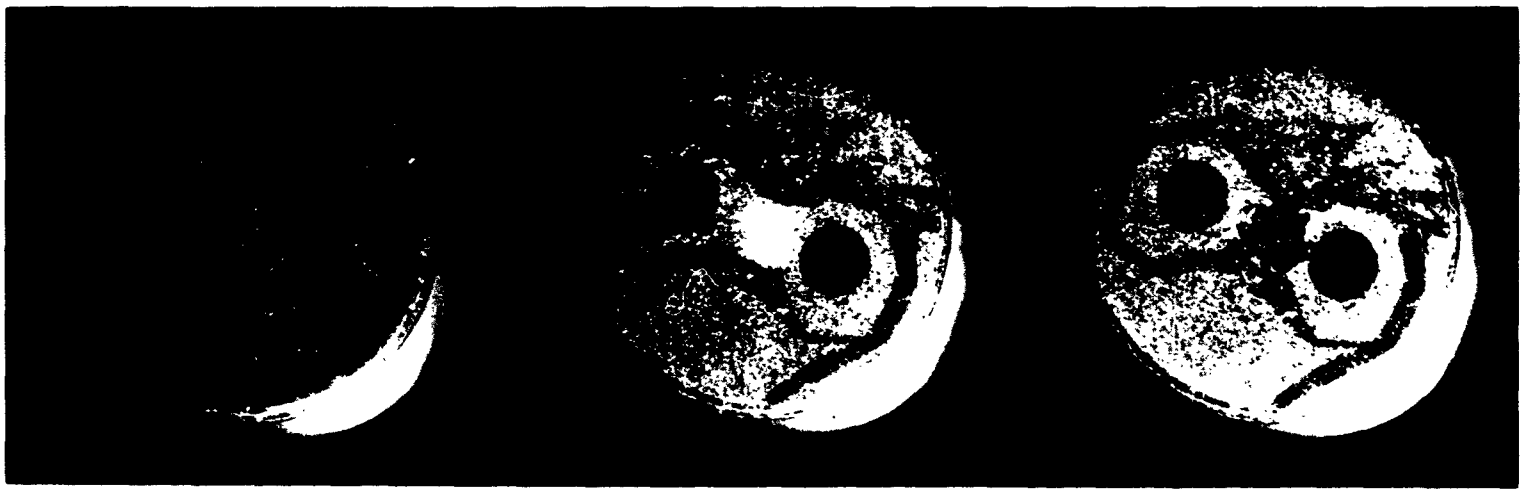


Figure 3. Glass Header Unit Before, During, and After the Heating Pulse.
(Magnification 10 Diameters)

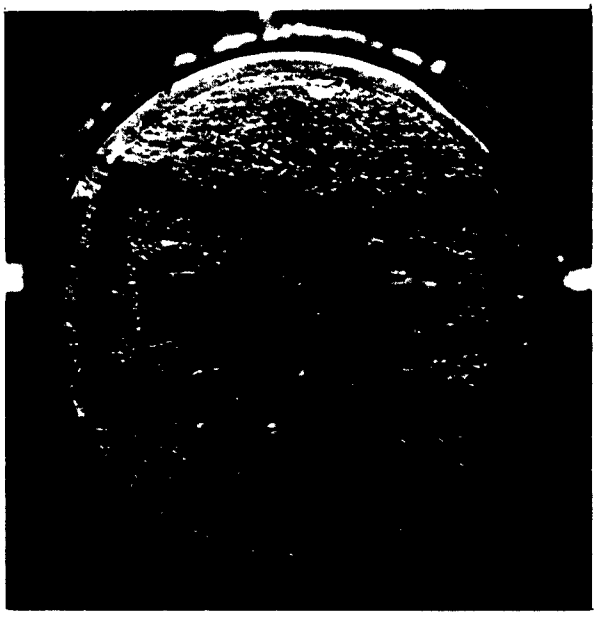
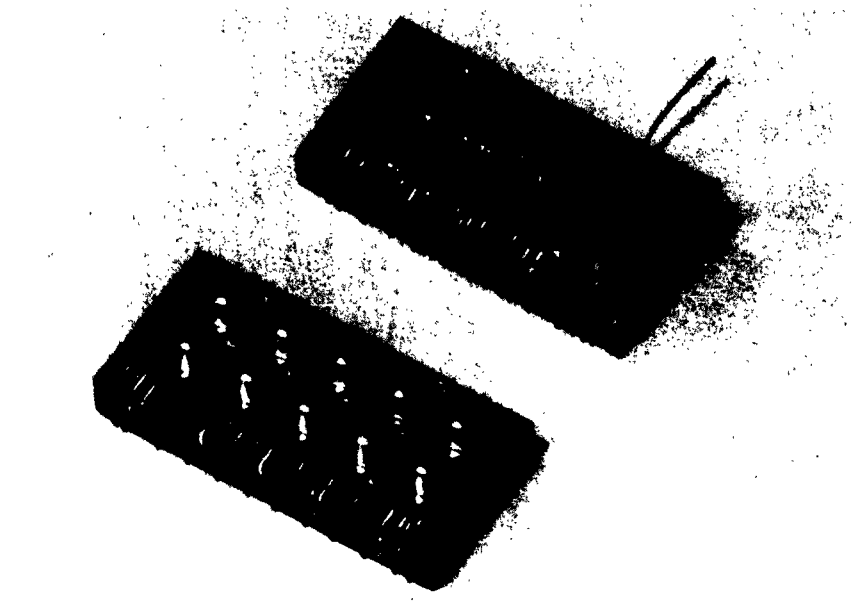


Figure 4. Narrowed Gold-Film Bridge Showing Breakdown Around Pin. (Magnification 14 Diameters)

TOP VIEW



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BOTTOM VIEW

Figure 5. Film Deposition Header Mounting Block.

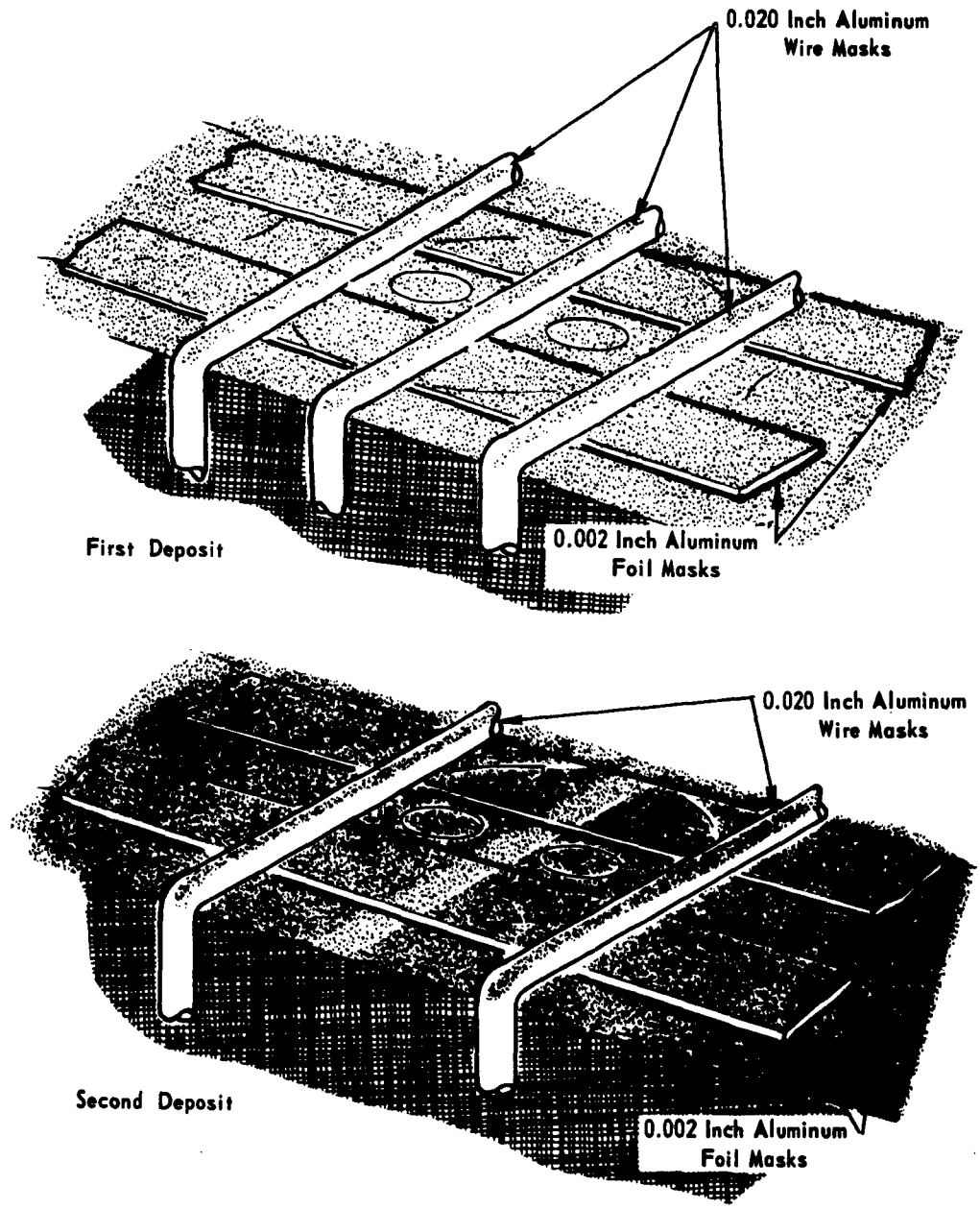

Figure 6. Detail of Masks for Deposition of Rectangular Film Bridge.

Figure 7. Header Mounting Blocks on Support Fixture.

Figure 8. Header Mounting Blocks in Vacuum Chamber.

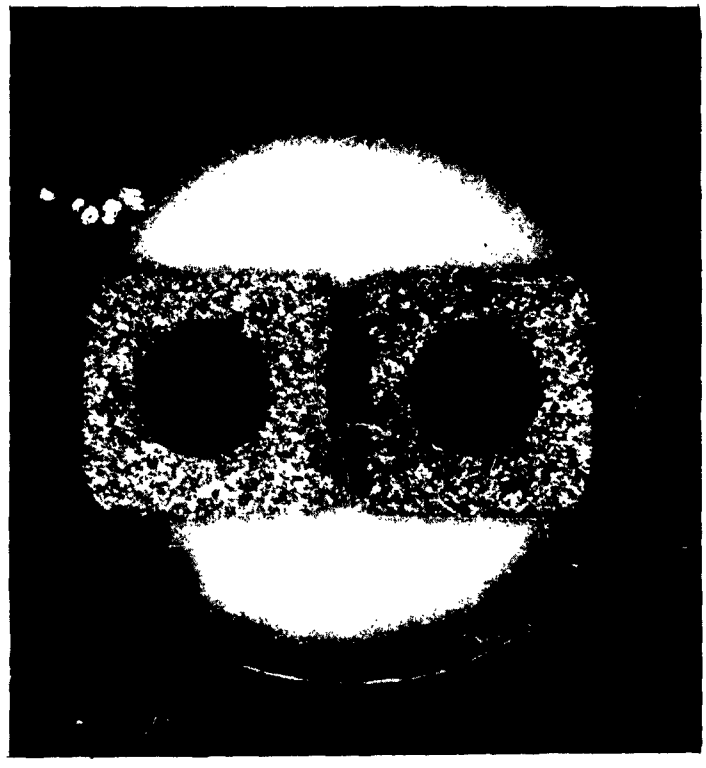

Figure 9. First Gold Film Deposit on BeO Header. (Scale has 5 mils/division)

4.2.3 Film Thickness

Based on the geometry of the evaporating system and the amount of metal evaporated, the film thickness is calculated to be 0.36 μ for the first deposit and 0.18 μ for the second. The total film thickness over the ends of the connecting pins is then 0.54 μ, with a thin region of 0.18 μ in the center. The thickness of the first film deposit was measured with a Model 64603 Carl Zeiss Interference Surface Tester, to give a measured thickness of 0.3 μ.

5. BRIDGE TEMPERATURE MEASUREMENT

Precise temperature measurement of the heated film by infrared methods is considered beyond the scope of the program. A measurement of this type poses problems sufficient to require a separate research program. The primary problems are: (1) the small area of heated surface available for temperature determination; (2) the relatively low temperatures of interest, from room temperature to approximately 500°C; and (3) the low emissivity of a heated metallic surface. These conditions require an extremely sensitive detector of high resolution.

The use of infrared photography to determine relative temperatures has been discussed with Aerojet photographic specialists. The amount of radiant energy available seems insufficient to be of practical value. The common glasses (lenses) are not satisfactory for wave lengths longer than 2.7 μ (Reference 8), and the temperatures of interest emit energies of longer wave lengths.

6. TEST PROGRAM

6.1 TEST INSTRUMENTATION

Initial bridge-resistance measurements were made with a No. 4285 Leeds and Northrup kelvin-bridge ohmmeter. The pulse firing circuit is shown in Figure 10.

The voltage level on the 1 μf capacitor was measured with a Keithley Electrometer Model 210. The pulse current and voltage measurements were recorded from a Type 551 Tektronix oscilloscope with a Beattie

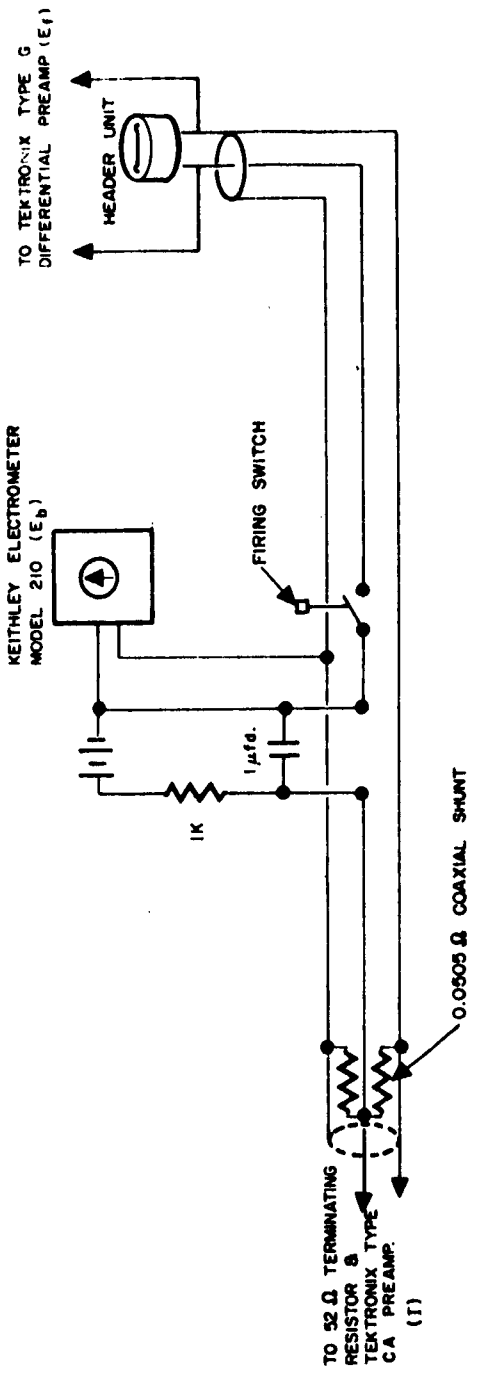

Figure 10. Pulse Firing Circuit.

Coleman K-2 camera. A Type CA preamplifier plug-in unit was used for current measurements, and a Type G differential preamplifier plug-in unit was used for voltage measurements. All connecting leads were made with coaxial cables and current measurements were obtained by means of a 0.0505-ohm T and M Research coaxial shunt.

The continuous-current test circuit is shown in Figure 11. These tests used the same oscilloscope instrumentation for recording data and were supplemented with a Weston Model 931 0-10 amp meter or a 20a/50mv Weston Meter shunt and a Sensitive Research Instrument Corporation "University" Model 0-50 mv meter for visual current monitoring and adjustment.

A copper-constantan thermocouple (0.010-in. -diameter wires) and a Leeds and Northrup 8662 portable precision potentiometer were used for heat-sink temperature measurements.

6.2 EXPLOSIVE AND EXPLOSIVE LOADING

The polyvinyl-alcohol lead azide used in the test program was purchased to Military Specification MIL-L-3055. A chemical analysis was made of this particular lot of explosive by the Kennard and Drake Chemical and Spectrographic Laboratories, with the following results:

Lead Azide	97.89%
Total Lead	70.09%
Acidity	None
Solubility in Water	0.41%

A particle-size distribution analysis was made in the Aerojet laboratories and is shown in Figure 12.

Nylon charge holders were cemented to the headers with Eastman 910 adhesive. Each of the test units was press-loaded at 5000 psi with 10 mg of the PVA lead azide. This amount did not completely fill the nylon charge holder. Since an indication of ignition was all that was desired, and because of the toxicity of BeO dust, the explosive charge was kept to a minimum.

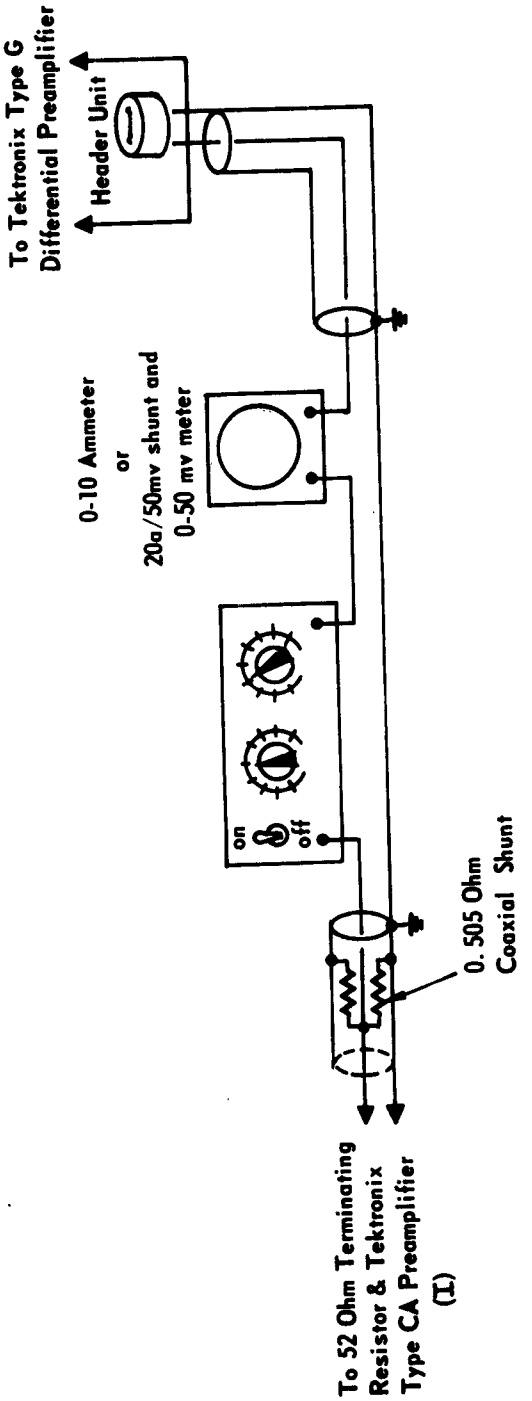

Figure 11. Continuous Current Firing Circuit.

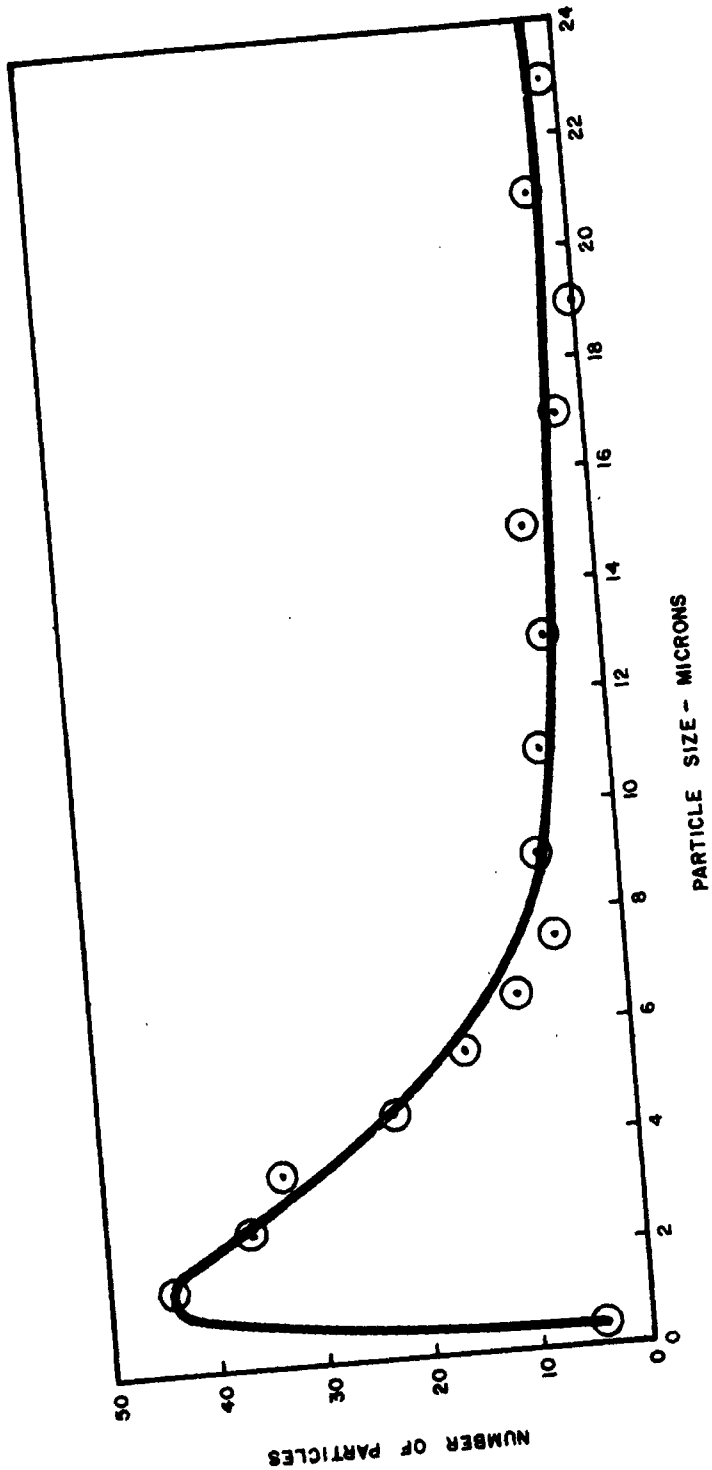

Figure 12. Particle Size Distribution of PVA Lead Azide.

6.3 EXPLORATORY TESTS

In the early stages of the program initial tests were performed with 0.002-in.-diameter platinum-iridium (90/10) bridgewires on glass headers and BeO transistor heat-sink wafers. Copper pins were cemented into the holes in the BeO wafers. The ends of the pins were made flush with the insulating surfaces and the bridgewires were soldered to the pin ends. Each bridgewire was held against the surface by placing a small Teflon block over it and holding it in place with a small spring clip. Various current levels were applied and the resistance change of the bridgewire was measured to provide an average BW temperature indication. Aluminum films with initial resistances similar to the BW were also deposited on these types of units, and the same measurements were made. The BeO wafers having aluminum films fractured when heated, producing unsatisfactory results. The data from these preliminary tests are shown graphically in Figure 13.

6.4 PRELIMINARY GLASS-HEADER FILM-BRIDGE TESTS

6.4.1 Nonexplosive Tests

The first double-deposit film-bridge test series was performed with glass headers having gold and aluminum films. The tests were conducted without explosive on the bridge. During these tests a change or lowering of the aluminum bridge resistance was noted when a pulse insufficient to burn out the films was applied. When these films were observed in a darkened room, small flashes or arcs were seen. The aluminum films have therefore been rejected for reasons of safety and reliability. However, this problem may possibly be overcome during further film-development studies.

6.4.1.1 Pulse Current Tests

The glass headers with gold and aluminum films were tested by discharging a 1 μf capacitor charged to various voltage levels through the film until burnout was obtained. The data on film burnout are presented in Table 1.

Data for a 0.002-in.-diameter gold wire and for a 90/10 platinum/iridium wire soldered on the header pins are also included for comparison.

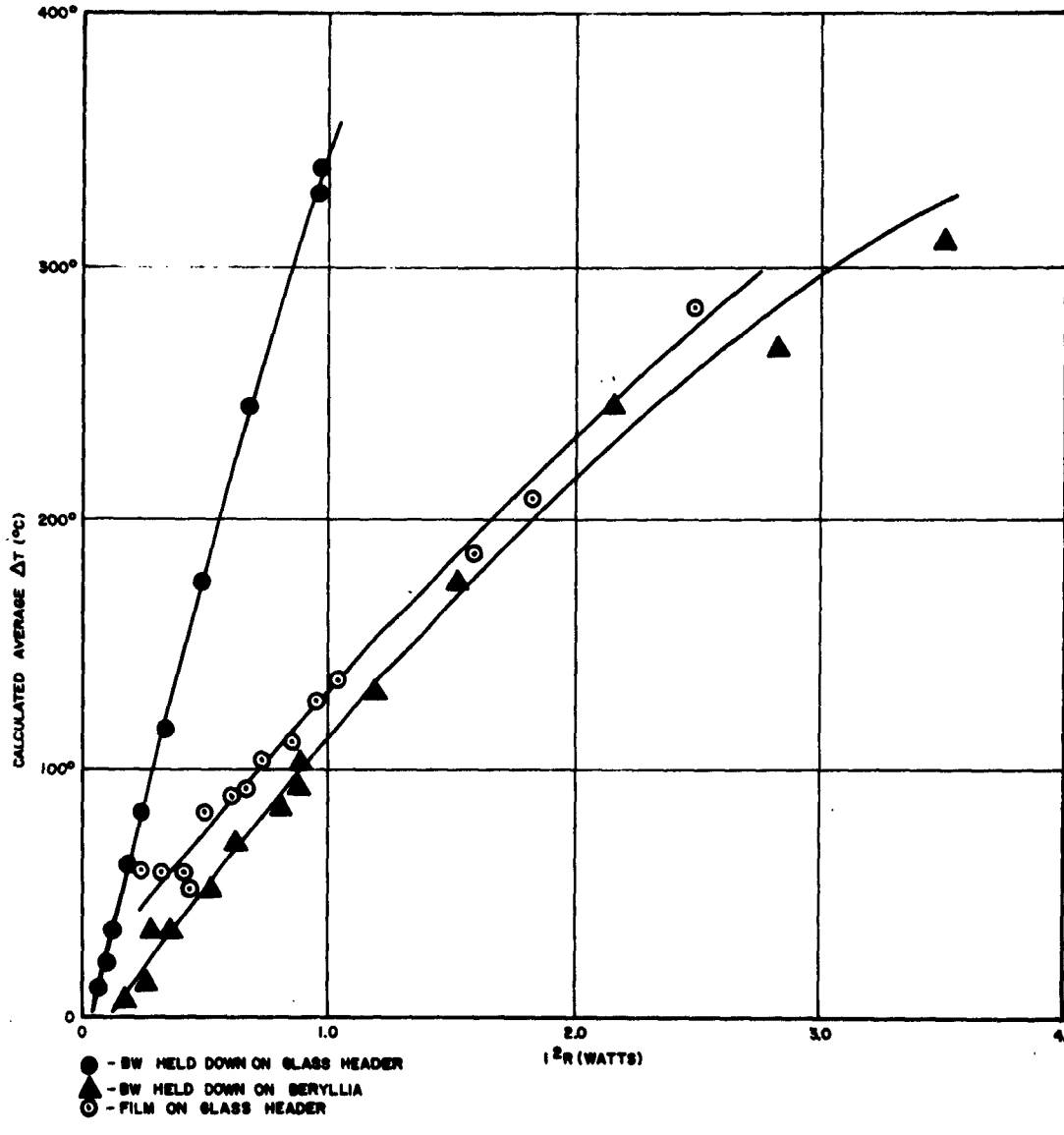

Figure 13. Exploratory BW and Film Tests.

Table 1. Pulse Heating Test.

Sample	Film Width (mils)	Initial Resistance (ohm)	Capacitor Voltage (v)	Peak Current (amp)	Time to Peak I (μsec)
Gold Films					
1-G	61	0.15	72	45	0.7
2-G	70	0.10	95	74	0.8
3-G	62	0.10	95	-	-
4-G	63	0.10	72	50	1.3
5-G	62	0.20	72	38	0.7
6-G	67	0.10	119	90	0.7
Aluminum Films					
7-A	102	0.1	380	375	1.0
8-A	95	0.1	380	380	0.8
9-A	97	0.13	388	390	1.0
10-A	110	0.1	351	360	1.2
15-A	96	0.15	294	400	1.0
Bridgewire					
Gold Wire	2 dia	0.03	400	500	1.5
Pt/Ir 90/10 Wire	2 dia	0.08	305	300	0.5

6.4.1.2 Continuous Current Tests

A limited number of tests was performed by gradually increasing the current from a 12-v storage battery through the film bridges until burnout occurred. The units were supported in a central hole in an aluminum strip 1/16 in. thick, 1-1/2 in. wide and about 12 in. long. This strip was bent into the shape of a U and attached to a camera so as to place the film bridge at the proper distance and location for taking microphotographs as shown in Figure 14. The strip was thus a heat sink and dissipated some thermal energy. The data from these tests are presented in Table 2.

Table 2. Continuous Current Tests.

Sample	Type Film	Film Width (mils)	Current at Burnout (amp)	Initial Resistance (ohm)
11-A	Al	100	6.8	0.090
12-A	Al	97	6.0	0.187
16-A*	Al	102	4.9	-
7-G	Au	72	3.5	0.10
8-G	Au	65	3.0	0.13

* Unit not supported in heat sink.

6.4.2 Explosive Tests

The explosive tests were performed with a 10 mg charge of PVA lead azide pressed at 5000 psi (D = 2.69 g/cc) into a nylon charge holder cemented onto the glass headers with Eastman 910 adhesive. The tests were performed

Figure 14. Header in Camera Fixture.

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in the same manner as the previously described tests without explosive. All film bridges were gold, and tests were also made with 0.002-in.-diameter platinum/iridium (90/10) bridgewires on the same type of glass headers. The results of the tests are presented in Tables 3 and 4 for the gold film bridges, and Tables 5 and 6 for the wire bridges.

Table 3. Gold Film Pulse Tests.

Sample	Film Width (mils)	Capacitor Voltage (volts)	Peak Current (amp)	Initial Resistance (ohms)	Time to Fire (μ sec)
13-G	73	100	70	0.188	1.8
11-G	73	86	58	---	1.1
17-G	74	95	50	0.176	0.8
18-G	73	86	45	0.168	0.6
10-G	66	86	52	0.175	1.8

Table 4. Gold Film Continuous Current Tests.

Sample	Film Width (mils)	Current at Ignition (amp)	Initial Resistance (ohms)
14-G	65	2.5	0.206
12-G	74	2.5	0.216
16-G	74	2.6	0.176

Table 5. Pt/Ir (90/10) 2 Mil BW Pulse Tests.

Sample	Capacitor Voltage (volts)	Peak Current (amp)	Initial Resistance (ohms)	Time to Fire (μsec)
1-W	260	200	0.174	
2-W	240	175	0.174	
3-W	240	175	0.185	
4-W	240	175	0.183	
5-W	240	175	0.185	
6-W	300	--	0.177	
7-W	300	235	0.182	2.4
4-ω	240	180	0.173	13.2
6-ω	255	185	0.155	4.0
7-ω	238	180	0.163	5.0

Table 6. Pt/Ir (90/10) 2 Mil BW Continuous Current Tests.

Sample	Current At Ignition (amp)	Initial Resistance (ohms)	Comments
5-ω	2.2	0.175	1.5 amp raised to 2.1 amp to fire
8-W	2.1	0.165	Fired on closing switch
9-W	2.02	0.185	Fired on closing switch
10-W	2.15	0.164	1.7 amp raised to 2.15 amp

6.5 COMPARATIVE TESTS, BeO AND GLASS HEADERS

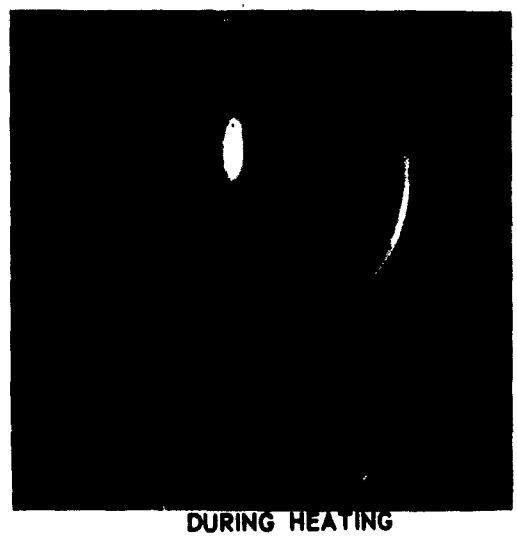
6.5.1 Bare Film

Pulse and continuous-current heating tests of the bare films (without explosive) were conducted on 9 glass and 11 BeO units. The units were tested in the camera-holding fixture as shown in Figure 14, except for Unit II BeO-6. Unit II BeO-6 was positioned in line with the lens and hole in the fixture so as not to make contact with the aluminum-strip heat sink, and the camera was refocused. Microphotographs were taken of each unit before, during and after heating (Figures 15 and 16). The test data are presented in Table 7 for the pulse tests and Table 8 for the continuous current tests.

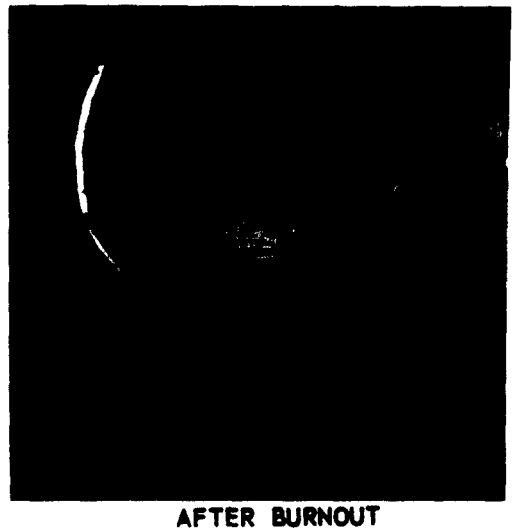
6.5.2 Explosive-Loaded Units

Nylon charge holders were cemented with Eastman 910 adhesive onto the gold-film bridged headers and press-loaded with PVA lead azide. The units were tested in the same manner as were the bare film bridges except that the units were tested within a firing chamber. Figures 17 and 18 show a unit mounted in the firing test fixture. The results of these tests are presented in Tables 9 and 10 for pulse-current tests, and Table 11 for the continuous-current tests. Only three continuous-current tests were performed with the beryllium oxide units because the heating of the entire header units softened or melted the nylon charge holders before the lead azide ignited. For this reason, future units will be fabricated with anodized aluminum charge holders replacing the nylon charge holders. The units, when tested, were held in contact with an aluminum-plate heat sink with a slight spring pressure, as shown in Figure 18. The heat-sink plate is 0.1 in. thick, 2.6 in. wide, and 3.5 in. high, and is mounted with two screws to the aluminum baffle plate. An iron constantan thermocouple was peened into a small hole in the plate adjacent to the counterbored hole into which the header unit is placed.

BEFORE HEATING

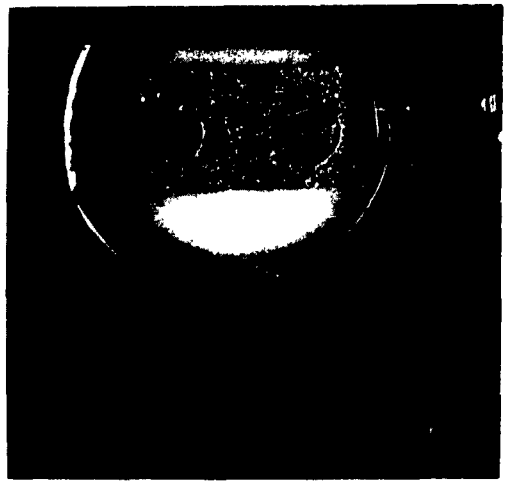


DURING HEATING



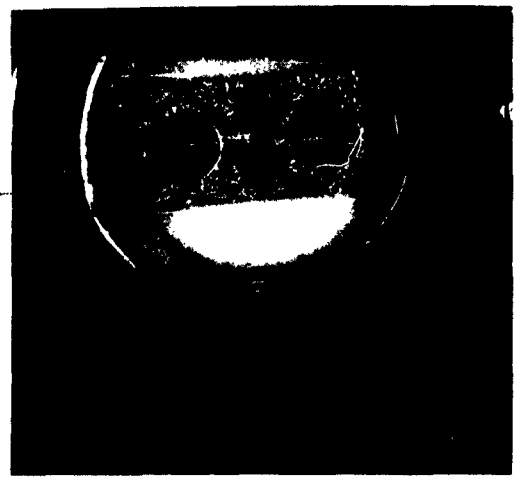
AFTER BURNOUT

Figure 15. Continuous Current Test Unit II BeO-1.
(Scale shown has 5 mils/division)



BEFORE PULSE

DURING PULSE



AFTER BURNOUT

Figure 16. Pulse Heating Test Unit III BeO-8.
(Scale shown has 5 mils/division.)

Table 7. Comparative Pulse Current Tests.

Samples	Pulse No.	Capacitor Voltage (volts)	Peak Current (amp)	Initial Resistance (Kelvin Bridge) (ohms)	Resistance at Burnout (oscilloscope) (ohms)	Time to Burnout (μsec)
Glass Units						
II G-7	1	90	80	0.104	-	-
	2	100	92	-	0.326	1
II G-10	1	100	90	0.112	-	-
	2	100	90	-	-	-
	3	100	88	-	0.205	1
III G-7	1	105	100	0.090	-	-
	2	117	110	-	-	-
	3	117	110	-	0.170	0.8
III G-9	1	102	90	0.125	-	-
	2	114	105	-	0.240	1.2
BeO Units						
I BeO-8	1	100	92	0.112	-	-
	2	123	120	-	-	-
	3	157	160	-	-	-
	4	157	155	-	0.160	1
I BeO-5*	1	157	145	0.157	-	1
II BeO-8	1	157	170	0.083	-	-
	2	181	200	-	-	-
	3	204	225	-	0.120	1
II BeO-5	1	180	200	0.081	-	-
	2	180	190	-	0.126	1
III BeO-8**	1	180	195	0.085	0.091	1.5

* Voltage trace exceeded oscilloscope range. Sample burned at edge of pin.
** Burnout occurred after current peak.

Table 8. Comparative Continuous Current Tests.

Samples	Current		Initial Resistance		Resistance At Burnout (ohms)	Approx Heating Time (sec)	Remarks
	Initial (amp)	At Burnout (amp)	Kelvin Bridge (ohms)	Oscilloscope (ohms)			
Glass Units							
I G-1	1.93	3.35	0.185	0.197	0.32	65	-
I G-3	2.06	3.35	0.143	0.170	0.28 est	90	Voltage exceeded oscilloscope range.
I G-7	2.42	3.80	0.116	0.136	0.25	90	-
II G-2	2.45	4.01	0.138	0.163	0.23	105	-
II G-3	2.85	4.7	0.095	0.109	0.19	100	-
BeO Units							
I BeO-2	2.60		0.136	0.135		225	Film did not burn out. Stopped heating to change ammeter to higher range.
I BeO-2	10.0	15.0	0.136			35	Voltage exceeded oscilloscope range.
I BeO-4	8.0	14.0	0.144	0.138		42	Voltage exceeded oscilloscope range.
I BeO-6	8.0	14.2	0.108	0.112	0.24	73	-
II BeO-1	8.2	15.0	0.092	0.089		220	-
II BeO-4	8.2	15.0	0.086	0.850	0.23	140	-
II BeO-6*	8.2	9.9	0.096	0.098	0.23	55	-

* This unit supported only by connecting pins with no heat sink. All other units were inserted into a central hole in a 1/16-in. -thick aluminum strip 1-1/2 in. wide and about 12 in. long.

Figure 17. Header, with Nylon Charge Holder, in Test Fixture.

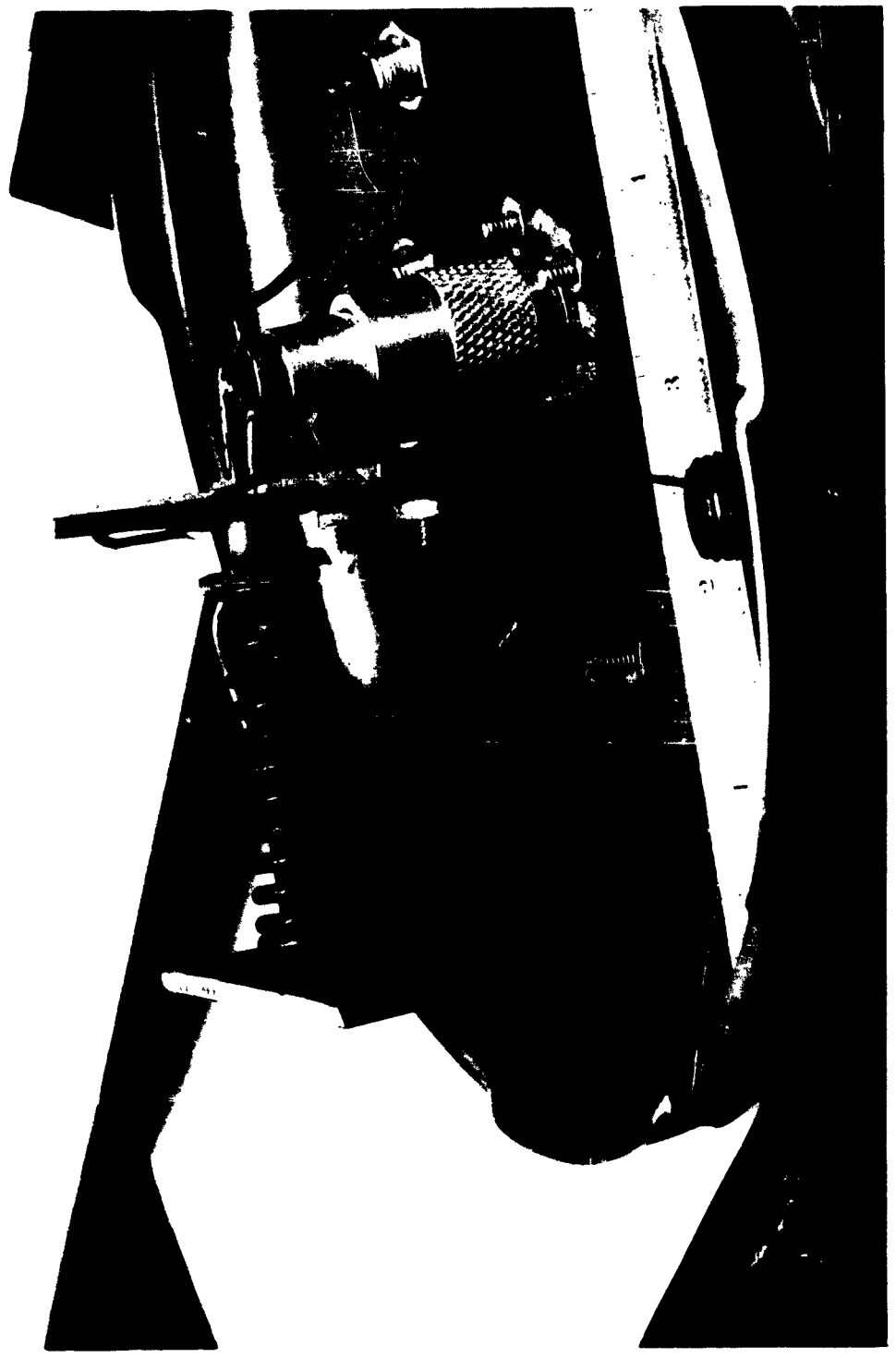


Figure 18. Header in Firing Test Fixture with Spring.

Table 9. Pulse Current Tests on BeO Headers.

Sample	Pulse No.	Capacitor Voltage (volts)	Peak Current (amp)	Initial Resistance (Kelvin Bridge) (ohms)	Resistance at Ignition (Oscilloscope) (ohms)	Bridge Voltage at Fire (volts)	Current at Fire (amp)	Time to Fire (μsec)	Remarks
A-I BeO-9	1	146	130	0.119	-	-	-	-	
	2	169	140	-	0.19	26	140	0.8	
A-I BeO-10	1	145	130	0.136	0.15	20	130	1.1	
A-II BeO-9	1	145	130	0.0865	-	-	-	-	
	2	155	140	-	-	-	-	-	
	3	166	145	-	-	-	-	-	
	4	172	155	-	-	-	-	-	
	5	184	170	-	0.16	25	160	1.4	
A-III BeO-5	1	161	145	0.119	0.16	23	145	1.2	
A-III BeO-10	1	161	140	0.109	0.14	18	125	1.5	
B-I BeO-3	1	149	130	0.115	0.15	19	130	1.0	
B-I BeO-5	1	142	122	0.120	0.15	18	120	1.3	
B-I BeO-7	1	142	125	0.102	-	-	-	-	
	2	148	132	-	0.14	17	125	1.4	
B-I BeO-9	1	142	127	0.109	-	-	-	-	Break in voltage trace slope.
	2	142	115	-	-	-	-	-	Point of firing indiscernible.
B-I BeO-10	1	132	110	0.117	(0.32)?	(26)?	(80)?	(1.7)?	Point of firing questionable.
B-II BeO-1	1	149	136	0.098	-	-	-	-	
	2	159	145	-	0.14	20	145	1.1	
B-II BeO-2	1	150	136	0.094	-	-	-	-	
	2	159	136	-	0.16	22	136	0.9	
B-II BeO-3	1	149	132	0.099	0.12	16	132	1.2	
B-II BeO-4	1	149	132	0.095	-	-	-	-	
	2	154	140	-	-	-	-	-	
	3	161	132	-	0.18	24	132	0.8	
B-II BeO-5	1	148	90	0.128	0.24	22	90	0.8	
B-III BeO-1	1	100	80	0.163	-	-	-	0.9	
	2	121	95	-	0.24	23	95	0.9	
B-III BeO-2	1	105	80	0.162	-	-	-	-	Break in voltage trace slope.
	2	104	70	-	0.41	23	56	0.5	Maximum current peak occurred after firing.
B-III BeO-3	1	105	84	0.133	-	-	-	-	
	2	115	94	-	-	-	-	-	
	3	122	100	-	-	-	-	-	
	4	127	88	-	0.23	20	88	0.6	
B-III BeO-4	1	104	80	0.150	-	-	-	-	
	2	114	95	-	-	-	-	-	Slight break in voltage trace slope.
	3	122	85	-	0.29	25	85	0.9	
B-III BeO-5	1	115	90	0.159	0.53	17	90	1.2	

Table 10. Pulse Current Tests on Glass Headers.

Sample	Pulse No.	Capacitor Voltage (volts)	Peak Current (amp)	Initial Resistance (Kelvin Bridge) (ohms)	Resistance at Ignition (Oscilloscope) (ohms)	Bridge Voltage at Fire (volts)	Current at Fire (amp)	Time to Fire (μsec)
A-III G-2*	1	95	74	0.120	-	-	-	-
	2	101	78	-	-	-	-	-
	3	106	85	-	0.44	14	32	2.2
A-III G-3	1	100	80	0.116	0.20	16	80	1.3
A-IV G-1	1	84	60	0.136	0.27	15	55	1.5
A-IV G-6	1	70	45	0.199	0.43	18	42	1.3
A-IV G-7	1	74	50	0.175	0.30	14	47	1.4
B-I G-1	1	98	50	0.210	0.45	17	38	0.4
B-I G-2	1	85	50	0.204	0.40	20	50	0.8
B-I G-4	1	88	54	0.173	0.32	16	50	0.7
B-I G-6	1	75	52	0.165	-	-	-	-
	2	82	60	-	0.28	17	60	1.0
B-I G-8	1	75	50	0.185	-	-	-	-
	2	80	44	-	0.47	17	36	0.5

* Unit fired late on 3rd pulse.

Table 11. Continuous Current Tests on Glass and BeO Headers.

Samples	Current Level (amp)	Initial Resistance (ohms)	Resistance at Fire (ohms)	Approx Heating Time (sec)	Remarks
A-III G-4	2	0.130	-	60	Heat sink temperature before test 26°C
	0	-	-	120	
	2.25	-	-	60	
	0	-	-	120	
	2.55	-	-	60	
	0	-	-	120	
	3.05	-	-	60	
	0	-	-	60	
	3.35	-	-	60	
	0	-	-	75	
	3.55	-	0.197	20	Heat sink temperature after firing 28°C
A-III G-6	2.65	0.118	-	60	Heat sink temperature before test 26°C
	0	-	-	60	
	3.00	-	-	60	
	0	-	-	90	
	3.25	-	-	60	
	0	-	-	60	
	3.6	-	-	60	
	0	-	-	60	
	3.9	-	-	60	
	0	-	-	60	
	4.15	-	-	60	
	0	-	-	60	
	4.35	-	0.172	34	Heat sink temperature after firing 29°C
A-IV G-3	4.2	0.145	0.181	~1	Heat sink temperature 27°C
A-IV G-4	~4.0	0.111	0.158	<1	Heat sink temperature 27°C
A-IV G-8	3.5	0.160	0.194	~1.5	Heat sink temperature 27°C
B-IV G-1	3.3	0.173	0.209	~2	Heat sink temperature 27°C
B-IV G-2	2.85	0.154	-	60	Heat sink temperature 27°C
	0	-	-	60	
	2.95	-	-	60	
	0	-	-	60	
	3.25	-	0.230	51	Heat sink temperature after firing 31°C
B-IV G-5	3.3	0.157	-	~1	Heat sink temperature 27°C. No oscilloscope picture.
B-IV G-6	3.05	0.108	0.23	8.5	Heat sink temperature 27°C
B-IV G-8	3.05	0.165	-	60	Heat sink temperature before test 27°C
	0	-	-	60	
	3.15	-	-	60	
	0	-	-	75	
	3.25	-	-	60	
	0	-	-	60	
	3.55	-	0.214	13	Heat sink temperature after firing 29°C
A-IV BeO-2	10.0	0.105	-	60	Nylon charge holder melted. Temperature of heat sink after firing 43°C
	0	-	-	60	
	11.0	-	0.200	28	
A-IV BeO-5	12.0	0.0975	-	3	Nylon charge holder melted. Temperature of heat sink after firing 42°C
	13.0	-	0.25	20	
A-IV BeO-9	12.6	0.125	0.183	8	Nylon charge holder melted. Temperature of heat sink after firing 33°C

7. SUMMARY AND CONCLUSIONS

The pulse-sensitive characteristics of a metal-film-bridged beryllium oxide header system have been demonstrated. It has been shown that a metal-film bridge (0.2 to 0.6 μ thick) can be successfully deposited onto the highly thermally conductive ceramic (BeO) surface of a header. Specifically, a system consisting of lead azide, gold film, BeO header, and heat sink has been shown to withstand 10 amp or 10 w of continuous power while being capable of initiation with a pulse from a charged 1 μf capacitor. The tests have indicated a capacitor mean firing voltage of 145 v with a standard deviation of 20 v.

The gold-film-bridged beryllium oxide substrate units are truly pulse sensitive and fire with approximately one-fourth the energy (from a 1 μf capacitor) required for a corresponding conventional wire-bridged glass substrate unit.

It is also significant that the gold-film-bridged glass system is pulse sensitive and fires with approximately one-ninth the energy (from a 1 μf capacitor) required for a corresponding conventional wire-bridged glass system.

The gold-film-bridged beryllium oxide system has been shown to tolerate continuous input-current levels from five to six times greater than those of a conventional wire-bridged glass system and from three to four times greater than those of a gold-film-bridged glass system. The gold-film-bridged glass system has been shown to tolerate continuous input-current levels from one and one-fourth to two times greater than those of a conventional wire-bridged glass system.

A 10 amp no-fire unit consisting of a beryllium oxide header bridged with a gold film and loaded with lead azide has been produced and shown to be feasible. This unit fired with an input-current of 11 amp. The power-dissipating capabilities can be further increased with a larger surface area of contact between the film-bridged beryllium oxide header and a heat sink.

The advantages of a film-bridged beryllium oxide system have been strikingly demonstrated with respect to its capability to dissipate power while still retaining its pulse-firing capability.

Tests are summarized in Table 12, and power levels at the time of ignition as a function of bridge resistance are illustrated in Figure 19.

Table 12. Test Summary

Type of Test Unit	Range of Continuous Current to Fire PVA Lead Azide (amp)	Range to Fire PVA Lead Azide with 1 μf Capacitor	
		Potential (volts)	Stored Energy $1/2\ CV^2$ (joules)
Au Film on Glass	2.5 to 4.4	70 to 106	2.45 to 5.61×10^{-3}
Au Film on BeO	11.0 to 13	104 to 184	5.41 to 16.9×10^{-3}
Pt/Ir Wire on Glass	2.0 to 2.2	240 to 300	28.8 to 45.0×10^{-3}

8. RECOMMENDATIONS

The significant results of the work on beryllium oxide as a thermally conducting but electrically nonconducting substrate in an electroexplosive device open up new and profitable areas of application.

It is recommended that advantage be taken of this technological breakthrough by further exploring the power-dissipating pulse-sensitive device developed during this investigation. Specifically, it is recommended that:

a. Bruceton tests with both pulse and continuous current be performed.

b. A pulse-firing test series with capacitors of values other than 1 μf be performed and evaluated.

c. Tests with thinner (higher resistance) gold-film bridges be performed.

d. Units be constructed to be tested and evaluated with RF-energy inputs.

A proposal for implementing these recommendations is being prepared for submittal.

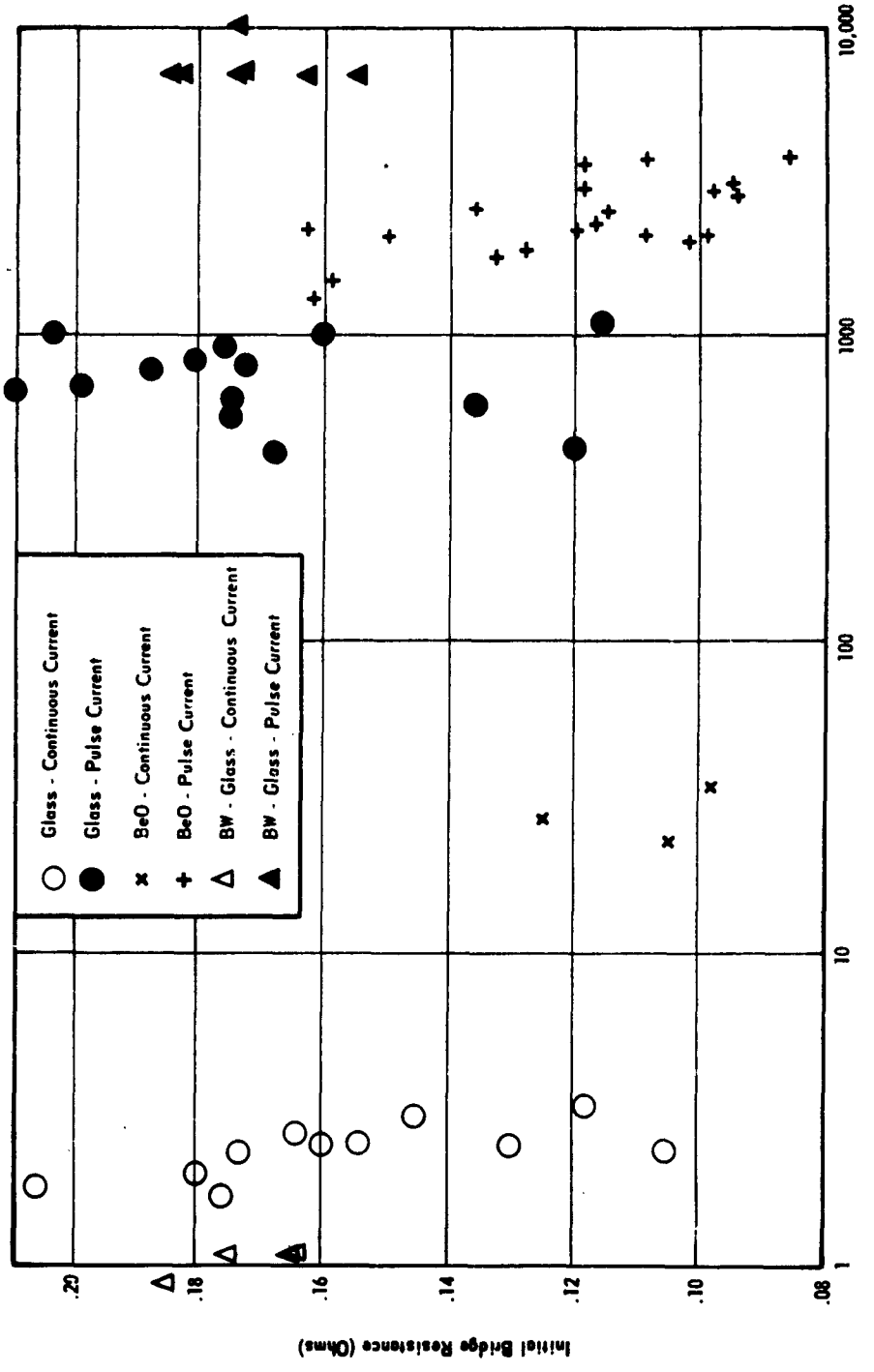


Figure 19. Power Level at Time of Ignition as a Function of Bridge Resistance.

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